HOW TO REPLICATE THE MECHANICAL BEHAVIOR OF BONE-IMPLANT SYSTEMS USING MICRO-CT BASED FINITE ELEMENT ANALYSES

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Introduction

Experimental mechanical tests to quantify the primary stability of trabecular bone screws typically require large sample sizes because of wide specimen-specific variation in bone quality. High-resolution computational analyses (microFE) are capable of capturing the microstructural variation in trabecular bone based on micro-CT imaging and could therefore be a potential complementary method to experimental mechanical testing. Indeed, we have shown that force-displacement curves, as measured experimentally, can be replicated using microFE. We have also shown that this requires the inclusion of a bone-screw interface (BSI) region with reduced mechanical properties [1]. At present, it is unclear how the specimen-specific tissue modulus of the BSI (E_BSI) can be quantified *a priori*. For the present study, we hypothesized that E_BSI is related to morphometric and mechanical parameters of bone at the implant site.

Methods

Ten trabecular bone specimens were core-drilled (16 mm in height and diameter) from fresh-frozen human femoral heads and scanned in a µCT scanner at 20 µm resolution. After insertion of a bone screw, all specimens were scanned again right before uniaxial quasi-static compression testing to failure. For the microFE analyses, tissue moduli of 120 GPa and 18 GPa were defined for the implant and bone, respectively. The tissue modulus of the BSI (E_BSI) was determined such that the computed implant/bone system stiffness, using the parallel FE solver 'ParoSol' [2], matched the experimentally measured stiffness. Subsequently, morphometric and mechanical properties of virtual bone biopsies were quantified for each specimen. Different cylindrically-shaped volumes of interest (VOIs) were defined in the peri-implant bone, with radii 0 mm to 4 mm from the implant surface. Morphometric parameters measured were bone volume fraction (BV/TV), specific bone surface (BS/BV), trabecular number (Tb.N.), trabecular thickness (Tb.Th.), trabecular spacing (Tb.Sp.) and structural model index (SMI). Mechanical parameters determined for the peri-implant bone of each biopsy were stiffness (Stiff) and apparent modulus (E_app). A multi-linear regression analysis (Matlab 2014a) was conducted to determine which of these parameters (maximum 5) would yield the best estimate for E_BSI. The predicted E_BSI was then used in the screw-bone model to quantify the predictive power for *in vitro* bone-implant stiffness.

Results

The best multi-linear predictive model for E_BSI was obtained for the VOI that included all bone within 3 mm distance to the implant. Input variables for this model were Stiff, Emod, BS/BV, SMI and Tb.Th; root-mean-square error (RMSE) for the predicted E_BSI was 0.063 GPa. When plugged into the microFE bone-screw models, the measured stiffness was accurately estimated with RMSE = 152 N/mm (3.5%), R^2=0.89, and a slope close to 1 (Fig. 1).

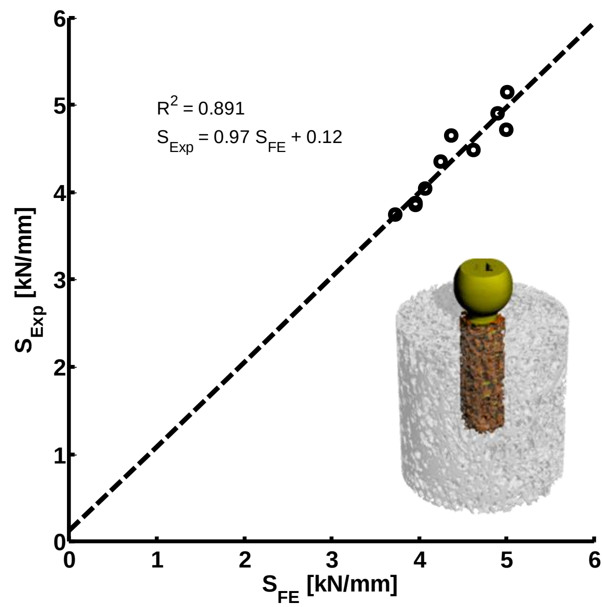

Figure 1: The micro-CT based FE models containing the individually predicted tissue moduli at the bone-screw interface region (orange color) are able to accurately replicate in vitro stiffness.

Discussion

A multi-linear regression model has been established that relates morphometric and mechanical parameters of bone biopsies at the implant site to the reduced tissue modulus of the bone-screw interface region. With this relationship in place, micro-CT based FE analyses can accurately replicate the measured apparent stiffness of bone-screw constructs.

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References

[1] J. Steiner (2015), Orthopedic Research Society Conference (accepted poster), Las Vegas, How Much Trabecular Bone Damage Is Induced By Screw Insertion?
[2] C. Flaig (2012), PhD Thesis ETH Zurich, A Highly Scalable Memory Efficient Multigrid Solver for µ-Finite Element Analyses.